(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 319 462 B1

(12) EUROPEAN PATENT SPECIFICATION

(45) Date of publication and mention of the grant of the patent:
08.12.2004 Bulletin 2004/50

(51) Int Cl.7: B23K 15/00

(21) Application number: 02258383.5

(22) Date of filing: 04.12.2002

(54) **Method of electron beam welding of single-crystal superalloys**

Elektronstrahlschweissverfahren von monokritallinen Superlegierungen

Procédé de soudage à faisceau d'électron de superalliages monocristallins

(84) Designated Contracting States:
CH FR IT LI SE

(30) Priority: 06.12.2001 US 10130

(43) Date of publication of application:
18.06.2003 Bulletin 2003/25

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Printed by Jouve, 75001 PARIS (FR)

Description

[0001] The present invention is directed to a method for electron beam welding at least two single-crystal superalloy articles containing significant amounts of refractory elements, by which the incidence of cracking is reduced in the resulting welded assembly.

[0002] Nickel-base superalloys are widely used to form components of gas turbine engines, including combustors and turbine vanes and blades. Superalloy components are often formed by casting, and for some applications are preferably or necessarily fabricated by welding as a result of their complexity. Welding is also widely used as a method for restoring blade tips, and for repairing cracks and other surface discontinuities in superalloy components caused by thermal cycling or foreign object impact.

[0003] Structural welds of nickel-base superalloy castings containing gamma-prime (γ') precipitates, and particularly those containing significant amounts of refractory elements such as tantalum, aluminum, molybdenum, tungsten, rhenium and niobium (columbium), are known to form strain age cracks upon cooling from welding or upon subsequent re-heating, such as during aging when the gamma prime phase is re-precipitated following solution heat treatment. As an example, the single-crystal nickel-base superalloy known as René N5, containing greater than 10 weight percent refractory elements, has been generally viewed as unweldable. The cause of cracks in superalloys such as René N5 is due at least in part to the residual stress produced during the welding and aging cycles.

[0004] Low heat input welding processes, such as laser or electron beam (EB) welding (collectively referred to herein as high energy beam welding) have been used to produce crack-free weld joints in single-crystal superalloys over a narrow range of welding conditions. An advantage of EB welding processes is that the high energy density of the focused electron beam is able to produce deep, narrow welds at high speed, making possible the formation of structural butt welds that add minimal additional weight. However, a drawback observed with laser beam and EB welding processes is directional grain growth in the fusion zone, which forms a distinct dendritic boundary in the center of the weld zone. This type of grain structure makes the joint vulnerable to centerline cracking, which reduces the fatigue strength of the welded component. Another problem encountered when high energy beam welding single-crystal superalloys is associated with the use of single-crystal backing strips beneath the abutting ends of a butt weld. Both of these defects are represented in Figure 1, which shows a welded assembly 10 comprising a pair of superalloy components 12 and 14 and a backing strip 16, in which the components 12 and 14 are joined by a butt weld joint 18. A centerline crack 20 is represented as being present in the joint 18, while a root crack 22 is shown in the backing strip 14.

[0005] High temperature TIG (tungsten inert gas) welding processes have been developed to overcome the centerline cracking problem associated with single-crystal superalloy joints formed by high energy beam welding. However, joint thickness and dimensions are limited by TIG processes, and their use is limited by the requirement for restrictive control of temperature, atmosphere and process parameters in order to produce a uniform grain structure for acceptable fatigue properties. Even then, there is the risk of excessive distortion and heat-affected zone (HAZ) cracking.

[0006] In EP-A-1 179 383 (Document according to Article 54(3) EPC) to Feng et al., EB welding is used in combination with a superalloy shim to form weld joints in single-crystal superalloys. Using a narrow range of welding conditions, the welding process disclosed by Feng et al. is able to avoid the formation of centerline cracks encountered by previous high energy beam welding processes. However, the high energy beam welding process disclosed by Feng et al. has not eliminated the development of root cracks where both components being welded are single-crystal superalloys, and particularly where the superalloys contain relatively high levels of refractory elements, as in the case of René N5.

[0007] EP-A-1 116 545, which is considered to represent the most relevant state of the art, describes a method of electron beam welding at least two single-cristal superalloy articles, in which these articles are welded together with a high energy beam operated at a travel speed of 0.4 to 2.0 cm/s, a voltage level of 30 to 150 kV and a current level of 1 to 40 mA, the electron beam melting the articles to cause mixing of the at least two articles, wherein the articles are cooled to yield a restricted welding zone.

[0008] In view of the difficulties discussed above, single-crystal superalloy assemblies have most often been formed from superalloys that are less prone to cracking, or assembled with fasteners or by brazing. However, the use of fasteners requires flanges and brazing typically requires a large interface (faying surface), both of which result in increased weight. Therefore, it would be desirable if a welding process existed for joining single-crystal nickel-base superalloys, particularly those containing 10 weight percent or more of refractory metals, and which was capable of producing a crack-free joint that exhibits improved fatigue life at high temperatures and strains.

[0009] The present invention generally provides a method for welding components formed of nickel-base superalloys, particularly single-crystal superalloys containing 10 weight percent or more of refractory metals, and to the resulting welded assemblies. The method of this invention reduces the incidence of cracking through the use of a electron beam welding process that makes use of a shim and particular welding parameters to develop a defect-free joint that exhibits improved fatigue life at high temperatures and high strain ranges.

[0010] The method of this invention involves electron beam welding single-crystal nickel-base superalloy articles according to claim 1, with the above-noted shim placed in a gap between the articles so that the shim contacts the

faying surfaces of the articles. A backing strip may be present that contacts both articles and bridges the gap between the articles. According to one aspect of the invention, the shim may be formed of a nickel-base superalloy that is more ductile than the nickel-base superalloys of the articles. The articles are welded together using a electron beam with a current pulse frequency of about 10 to 50 Hz and a travel speed of about 0.85 to about 1.5 cm/s. The electron beam causes the shim and portions of the articles contacting the shim to melt, and the superalloys of the shim and articles to mix. According to the invention, the frequency and speed parameters of the welding process cause the resulting weld joint to form multiple roots that extend into the backing strip (if present).

[0011] A preferred aspect of the invention is the elimination of both centerline and root cracks in the weld joint and, in the case of a butt weld, full penetration of the weld joint. Other advantages of the invention include reducing part distortion and a simplified process in the production of superalloy joints for complex structures, including airfoils for gas turbine engine applications.

[0012] Other objects and advantages of this invention will be better appreciated from the following detailed description.

[0013] The invention will now be described in greater detail, by way of example, with reference to the drawings, in which:-

Figure 1 is a cross-sectional representation of a weld joint of two single-crystal superalloy components with a superalloy backer, and indicates the location of centerline and root cracks in the weld joint.

Figures 2 and 3 are cross-sectional representations of a process for forming a crack-free weld joint between two single-crystal superalloy components with a superalloy backer in accordance with a preferred embodiment of this invention.

Figure 4 is a micrograph of a cross-section through a crack-free weld joint formed between two single-crystal superalloy components in accordance with the preferred embodiment of this invention.

[0014] The present invention is a process for electron beam welding nickel-base superalloy articles, and particularly single-crystal gamma prime-strengthened nickel-base superalloy castings, without the creation of cracks in the resulting weld joint. The advantages of this invention is described with electron beam (EB) welding and the fabrication of superalloy components of gas turbine engines. However, the invention can also be applied to a variety of welded assemblies formed from nickel-base superalloy castings.

[0015] In the past, certain superalloy components for gas turbine applications were either fabricated by welding together castings of high-temperature materials other than gamma prime-strengthened nickel-base superalloys, or limited to being assembled with fasteners or by brazing, both of which incur unwanted additional weight. According to the present invention, gamma prime-strengthened nickel-base superalloy castings can be successfully EB welded without the occurrence of cracking during cooling. The benefits of this invention are particularly notable for gamma prime-strengthened nickel-base superalloys containing one or more refractory metals, which at combined levels of about ten weight percent and more render such superalloys particularly prone to centerline and root cracks. A notable example of such a superalloy is René N5, which has a nominal composition, by weight, of about 7.5% Co, 7.0% Cr, 6.5% Ta, 6.2% Al, 5.0% W, 3.0%Re, 1.5% Mo, 0.15% Hf, 0.05% C, 0.004% B, 0.01 % Y, the balance nickel and incidental impurities.

[0016] As represented in Figure 2, the invention makes use of a shim 24 placed between two components 12 and 14 to be welded, so that the shim 24 contacts faying surfaces 26 and 28 of the components 12 and 14. As shown in Figure 2, the shim 24 protrudes beyond adjacent surfaces 30 and 32 of the components 12 and 14. As may be required for the particular assembly, a backing strip 16 is shown as contacting the lower surfaces 34 and 36 of the components 12 and 14, and bridges the gap filled by the shim 24. The shim 24 is preferably formed of a nickel-base superalloy that is more ductile than the nickel-base superalloys of the components 12 and 14. For example, if the components 12 and 14 are formed of gamma prime-strengthened nickel-base superalloys, the shim 24 may be formed of a nickel-base superalloy that does not contain gamma prime precipitates, an example of which is Inconel 617 with a nominal composition, by weight, of about 22% Cr, 12.5% Co, 9.0% Mo, 1.0% Al, 0.3% Ti, 0.07% C, the balance nickel and incidental impurities.

[0017] Figure 3 represents the result of the components 12 and 14 being welded together using an electron beam 38 (Figure 2). Parameters required for the ES welding process include operating the electron beam 38 at a low frequency current pulse and a low travel speed. More particularly, the pulsed current frequency is about 10 to 50 Hz, preferably about 10 to about 20 Hz, and the travel speed is about 0.85 to about 1.5 cm/s (about 20 to 35 inches per minute) preferably about 0.85 to about 1.1 cm/s (20 to about 25 inches per minute). Other important process parameters include a voltage level of about 100 to about 150 kV, preferably about 100 to about 120 kV, and a current level of about 10 to 40 milliamps, preferably about 20 to about 25 milliamps. The beam 38 may be sharply focused to about 150 micrometers

(about 0.006 inch) beyond a sharp focus (i.e., out of focus), and oscillated in a circular pattern with a diameter of about 0.76 to about 3.8 mm (about 0.03 to about 0.15 inch) preferably about 1.8 mm (about 0.070 inch) which together serve to evenly distribute the beam energy across the weld area.

[0018] Under the above-stated process conditions, the electron beam 38 causes the shim 24 and portions of the components 12 and 14 contacting the shim 24 to melt, such that the superalloy compositions of the shim 24 and components 12 and 14 mix within the resulting polycrystalline butt weld joint 40 (Figure 3). As a result of the shim 24 protruding beyond the adjacent surfaces 30 and 32 of the components 12 and 14 (Figure 2), a positive crown of weld metal is present at the weld surface that eliminates surface defects. A particular characteristic of the welding process of this invention is that, on cooling, the weld joint 40 has a joint root 42 with multiple roots 44 that extend into the backing strip 16. More particularly, the roots 42 extend into the backing strip 16 beneath the original interface between the shim 24 and faying surfaces 26 and 28. In Figure 3, the joint root 42 is represented as generally having a W-shape. In Figure 4, which is a microphotograph of a weld joint formed in accordance with this invention, a joint root is seen to have an inverted W-shape as a result of three roots extending into a backing strip. The outer roots extend into the backing strip beneath the original interface between the shim and faying surfaces of the joined bodies (from the vicinity of the existing interfaces between the weld joint and the welded bodies), while the third root extends centrally into the backing strip.

[0019] The present invention has associated W-shaped root joints of the type shown in Figures 3 and 4 with the elimination of root cracks (e.g., 22 in Figure 1), corresponding to improved fatigue life at high temperatures and high strains. While voltage level, current level, beam focus, and beam oscillation are all important parameters of the welding process, the low travel speed of the beam and particularly the low frequency of the current pulse have been directly linked to the ability to produce the W-shaped joint roots desired by this invention. For example, while the voltage, current and travel speed of this invention overlap those of EP-A-1 179 383 (Article 54/3) EPC Document) to Feng et al., the latter process does not produce the W-shaped joint roots of this invention, and therefore does not eliminate root cracks of the type shown in Figure 1. Furthermore, the Feng et al. welding process did not recognize current pulse frequency as a result-effective variable, i.e., a variable that achieves a recognized result relative to eliminating joint cracks.

[0020] The EB welding process of this invention is performed in an atmosphere suitable for prior art EB welding processes. As known in the art, a suitable vacuum level is necessary to prevent electron scattering and rapid oxidation of the EB welding filament. A suitable vacuum level is believed to be about 10^{-4} Torr (about 0.013 Pa), though pressures of as high as about 10^{-3} Torr (about 0.13 Pa) could be employed with acceptable results. Prior to welding, the components 12 and 14 are preferably preheated to a temperature generally up to the solution heat treatment temperature for the particular superalloy, such as within about 200°C of the solution temperature. For gamma prime-strengthened superalloys, the preheat temperature is preferably at or near the gamma prime precipitation (solvus) temperature in order to avoid creep while providing stress relief prior to cooling. As known in the art, solution heat treatments for gamma prime-strengthened nickel-base superalloys are performed at temperatures above the superalloy solvus temperature, at which gamma prime precipitates enter solid solution. Gamma prime solvus temperatures for nickel-base superalloys are typically in the range of about 1150°C to about 1300°C (about 2100-2370°F). Rapid quenching from the solution (supersolvus) temperature produces a supersaturated solution, after which aging can be performed to re-precipitate the hardening gamma prime phase in a controlled manner.

[0021] While maintaining the above vacuum and temperature conditions, the components 12 and 14 are EB welded to produce the weld joint 40. Particularly suitable welding parameters within the ranges stated above will depend on, among other things, the thicknesses of the components 12 and 14 at the point they are to be joined.

[0022] In an investigation leading up to this invention, two single-crystal castings formed of René N5 superalloy and a shim formed of IN617 were assembled in the manner represented in Figure 2. The thicknesses of the castings at the desired weld joint were about 0.76 cm (about 0.3 inch). The shim was about 0.10 cm (about 0.04 inch) thick, had a width of about 0.81 cm (about 0.32 inch) such that it projected about 0.05 cm (about 0.02 inch) above the surfaces of the castings. A backing strip formed of single-crystal René N5 was positioned beneath the shim and castings, and bridged the gap between the castings filled by the shim. The thickness of the backing strip was about 0.38 cm (about 0.15 inch). Using a commercially-available EB weld machine maintained at a vacuum of about 10^{3} Torr (about 7.5×10^{6} Pa) and a temperature of about 25°C, an out-of-focus electron beam was projected onto the shim and the immediately surrounding regions of the castings. The welding parameters included a voltage level of about 120 kV, a current level of about 24 milliamps, a pulsed current frequency of about 10 Hz, and a travel speed of about 0.85 cm/s (about 20 inches per minute). During welding strong mixing and stirring between the casting and shim materials took place. The welded assembly was then cooled to room temperature and heat treated under conditions appropriate for René N5. The resulting weld metal composition is summarized by weight in Table 1 below.

TABLE 1.

Element	Weld Center	IN617 (shim)	René N5 (castings)
Al	4.05	1	6.2
Mo	2.76	9	1.5
Cr	14.02	22	7
Co	9.33	12	7.5
Ti	0.01	0.3	-
Ta	4.46	-	6.5
S	0.00	-	-
Fe	0.05	-	-
W	3.39	-	5
Re	2.18	-	3
Hf	-	-	0.15
C	-	0.07	0.05
B	-	-	0.004
Y	-	-	0.01
Ni	Balance	Balance	Balance

[0023] As a result of the EB welding technique of this invention, the welded castings and weldment were essentially free of thermally-induced cracks after cooling and remained crack-free after heat treating. Particularly notable as being absent were centerline cracks in the weld and root cracks in the backing strip. While not wishing to be held to any particular theory, from the results of this investigation it was concluded that root cracks occur in backing strips formed of single-crystal superalloys as a result of the electron beam striking the backing strip, and that the combination of a low current pulse frequency and low travel speed produced a W-shaped joint root (Figures 3 and 4) that was linked through the investigation to a reduced risk of root cracks, possibly as a result of better distributed stresses in the backing strip. The strong mixing and stirring that occurred during welding between the casting and shim materials were believed to inhibit centerline cracking in the weld joint.

[0024] From Table 1, it can be seen that the weld metal has become a gamma prime precipitation-hardening alloy with the composition similar to that of Inconel 738 (nominal composition, by weight, of 16% chromium, 8.5% cobalt, 1.75% molybdenum, 2.6% tungsten, 1.75% tantalum, 0.9% niobium, 3.4% aluminum, 3.4% titanium, 0.10% zirconium, 0.01% boron, 0.17% carbon, the balance nickel and impurities). The presence of the gamma prime precipitates (principally $Ni_3(Al,Ta)$) ensures adequate creep strength and low cycles fatigue (LCF) life for the joint at high temperatures. Subsequent LCF testing performed at a strain level of about 0.7% showed that the LCF life of the joints welded in accordance with the present invention was about four times longer than that of weld joints formed on identical hardware by TIG welding processes.

[0025] In view of the above, it can be seen that the present invention enables EB welding of gamma prime-strengthened single-crystal nickel-base superalloy articles without resulting in stress-induced cracks upon cooling.

Claims

1. A method of electron beam welding at least two single-crystal superalloy articles (12,14), the method comprising the steps of:

   placing a shim (24) in a gap between the articles (12,14) so that the shim (24) contacts faying surfaces (26,28) of the articles (12,14), the shim (24) being formed of a superalloy that is more ductile than the superalloys of the articles (12,14);
   welding the articles (12,14) together with a high-energy beam (38) operated at a pulsed current frequency of about 10 to 50 Hz, a travel speed of about 0.85 to about 1.5 cm/s, a voltage level of about 100 to about 150 kV, and a current level of about 10 to 40 milliamps, the high-energy beam (38) melting the shim (24) and portions of the articles (12,14) contacting the shim (24) to cause mixing of the superalloys of the shim (24) and articles (12,14); and then
   cooling the articles (12,14) to yield a weld joint (40) having a W-shaped joint root (42).

2. A method according to claim 1, wherein the superalloys of the articles (12,14) are nickel-base superalloys containing at least ten weight percent of one or more refractory metals.

3. A method according to claim 1, wherein the superalloys of the articles (12,14) are strengthened by gamma-prime precipitates.

4. A method according to claim 3, wherein the superalloy of the shim (24) does not contain gamma-prime precipitates, and the weld joint (40) contains gamma-prime precipitates.

5. A method according to claim 1, wherein the shim (24) protrudes beyond adjacent surfaces (30,32) of the articles (12,14).

6. A method according to claim 1, further comprising providing a backing strip (16) that contacts the articles (12,14) and bridges the gap between the articles (12,14), the W-shaped joint root (42) being formed within the backing strip (16).

7. A method according to claim 6, wherein the backing strip (16) has a single-crystal microstructure.

8. A method according to claim 1, wherein the superalloys of the articles (12,14) have a nominal composition, by weight, of about 7.5% Co, 7.0% Cr, 6.5% Ta, 6.2% Al, 5.0% W, 3.0%Re, 1.5% Mo, 0.15% Hf, 0.05% C, 0.004% B, 0.01% Y, the balance nickel and incidental impurities.

9. A method according to claim 1, wherein the superalloy of the shim (24) has a nominal composition, by weight, of about 22% Cr, 12.5% Co, 9.0% Mo, 1.0% Al, 0.3% Ti, 0.07% C, the balance nickel and incidental impurities.

10. A method according to claim 1, wherein the weld joint (40) is a butt weld.

Patentansprüche

1. Verfahren zum Elektronenstrahlschweissen von wenigstens zwei Einkristall-Superlegierungs-Gegenständen (12,14), wobei das Verfahren die Schritte enthält:

   Anordnen einer Lehre (24) in einem Spalt zwischen den Gegenständen (12,14) derart, dass die Lehre (24) fluchtende Oberflächen (26,28) der Gegenstände (12,14) kontaktiert, wobei die Lehre (24) aus einer Superlegierung gebildet wird, die duktiler als die Superlegierungen der Gegenstände (12,14) ist,
   Zusammenschweissen der Gegenstände (12,14) mit einem hochenergetischen Bündel (38), das bei einer gepulsten Stromfrequenz von etwa 10 bis 50 Hz, einer Wanderungsgeschwindigkeit von etwa 0,85 bis etwa 1,5cm/sek. einem Spannungspegel von etwa 100 bis etwa 150 kV und einem Strompegel von etwa 10 bis 40 Milliampere betrieben wird, wobei das hochenergetische Bündel (38) die Lehre (24) und die Lehre kontaktierende Abschnitte der Gegenstände (12,14) schmilzt, um ein Mischen der Superlegierungen der Lehre (24) und der Gegenstände (12,14) zu bewirken, und dann
   Abkühlen der Gegenstände (12,14), um eine Schweissverbindung (40) mit einem W-förmigen Schweisasfuss (42) zu erzielen.

2. Verfahren nach Anspruch 1, wobei die Superlegierungen der Gegenstände (12,14) Nickelbasis-Superlegierungen sind, die wenigstens zehn Gewichtsprozent von einem oder mehreren hochwarmfesten Metallen enthalten.

3. Verfahren nach Anspruch 1, wobei die Superlegierungen der Gegenstände (12,14) durch Gamma-Strich Ausscheidungen verstärkt sind.

4. Verfahren nach Anspruch 3, wobei die Superlegierung der Lehre (24) keine Gamma-Strich Ausscheidungen enthält und die Schweissverbindung (40) Gamma-Strich Ausscheidungen enthält.

5. Verfahren nach Anspruch 1, wobei die Lehre (24) über benachbarte Oberflächen (30,32) der Gegenstände (12,14) vorsteht.

6. Verfahren nach Anspruch 1, wobei ferner ein Stützstreifen (16) vorgesehen wird, das die Gegenstände (12,14)

kontaktiert und den Spalt zwischen den Gegenständen (12,14) überbrückt, wobei der W-förmige Schweissfuss (42) in dem Stützstreifen (16) gebildet wird.

7. Verfahren nach Anspruch 6, wobei der Stützstreifen (16) eine einkristalline Mikrostruktur hat.

8. Verfahren nach Anspruch 1, wobei die Superlegierungen der Gegenstände (12,14) eine nominale Zusammensetzung, in Gewichtsprozent, von etwa 7,5% Co, 7,0% Cr, 6,5% Ta, 6,2% Al, 5,0% W, 3,0% Re, 1,5% Mo, 0,15% Hf, 0,05% C, 0,004% B, 0,01% Y, den Rest Nickel und zufällige Verunreinigen enthalten.

9. Verfahren nach Anspruch 1, wobei die Superlegierung der Lehre (24) eine nominale Zusammensetzung, in Gewichtsprozent, von etwa 22% Cr, 12,5% Co, 9,0% Mo, 1,0% Al, 0,3% Ti, 0,07% C, den Rest Nickel und zufällige Verunreinigungen enthält.

10. Verfahren nach Anspruch 1, wobei die Schweissverbindung (40) eine Stossschweissung ist.

Revendications

1. Procédé permettant de souder, à l'aide d'un faisceau d'électrons, au moins deux pièces (12, 14) en superalliage monocristallin, lequel procédé comporte les étapes suivantes :

   - placer une cale (24) dans l'interstice entre les pièces (12, 14) de manière à ce que cette cale (24) touche les surfaces affleurantes (26, 28) des pièces (12, 14), laquelle cale (24) est en un superalliage plus ductile que les superalliages des pièces (12, 14) ;
   - souder ensemble les pièces (12, 14) à l'aide d'un faisceau à haute énergie (38) fonctionnant avec une fréquence de courant pulsé d'à peu près 10 à 50 Hz, une vitesse de déplacement d'à peu près 0,85 à 1,5 cm/s, une tension d'à peu près 100 à 150 kV et une intensité de courant d'à peu près 10 à 40 mA, lequel faisceau à haute énergie (38) fait fondre la cale (24) et les zones des pièces (12, 14) qui touchent la cale (24), ce qui fait que les superalliages de la cale (24) et des pièces (12, 14) se mélangent ;
   - et faire ensuite refroidir les pièces (12, 14) pour obtenir un joint de soudure (40) dont la racine (42) a la forme d'un W.

2. Procédé conforme à la revendication 1, dans lequel les superalliages des pièces (12, 14) sont des superalliages à base de nickel qui contiennent au moins 10 % en poids d'un ou de plusieurs métaux réfractaires.

3. Procédé conforme à la revendication 1, dans lequel les superalliages des pièces (12, 14) sont renforcés par des précipités de phase γ'.

4. Procédé conforme à la revendication 3, dans lequel le superalliage de la cale (24) ne contient pas de précipités de phase γ', mais le joint de soudure (40) contient des précipités de phase γ'.

5. Procédé conforme à la revendication 1, dans lequel la cale (24) fait saillie par rapport aux surfaces adjacentes (30, 32) des pièces (12, 14).

6. Procédé conforme à la revendication 1, qui comporte en outre le fait de disposer un support à l'envers (16) qui touche les pièces (12, 14) et enjambe l'interstice entre les pièces (12, 14), et dans lequel la racine de joint en W (42) est formée dans le support à l'envers (16).

7. Procédé conforme à la revendication 6, dans lequel le support à l'envers (16) possède une microstructure monocristalline.

8. Procédé conforme à la revendication 1, dans lequel la composition nominale des superalliages des pièces (12, 14) est à peu près la suivante, en pourcentages pondéraux : 7,5 % de cobalt, 7,0 % de chrome, 6,5 % de tantale, 6,2 % d'aluminium, 5,0 % de tungstène, 3,0 % de rhénium, 1,5 % de molybdène, 0,15 % de hafnium, 0,05 % de carbone, 0,004 % de bore et 0,01 % d'yttrium, le complément étant du nickel et des impuretés fortuites.

9. Procédé conforme à la revendication 1, dans lequel la composition nominale du superalliage de la cale (24) est à peu près la suivante, en pourcentages pondéraux : 22 % de chrome, 12,5 % de cobalt, 9,0 % de molybdène, 1,0

% d'aluminium, 0,3 % de titane et 0,07 % de carbone, le complément étant du nickel et des impuretés fortuites.

10. Procédé conforme à la revendication 1, dans lequel le joint de soudure (40) forme une soudure bout à bout.

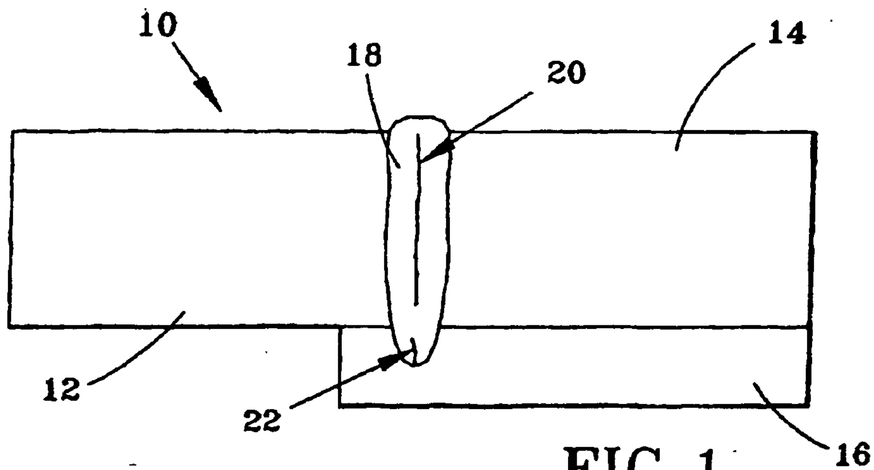

FIG.1
(Prior Art)

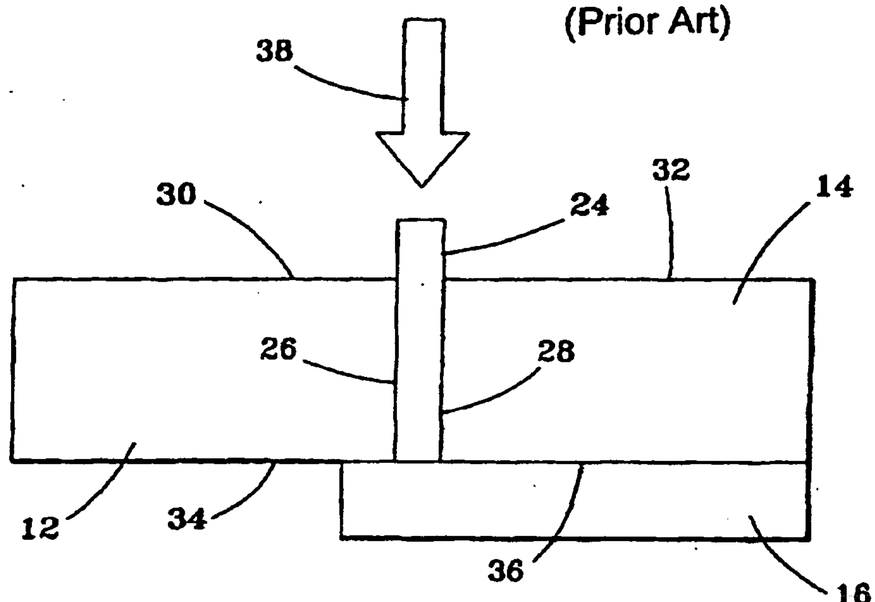

FIG.2

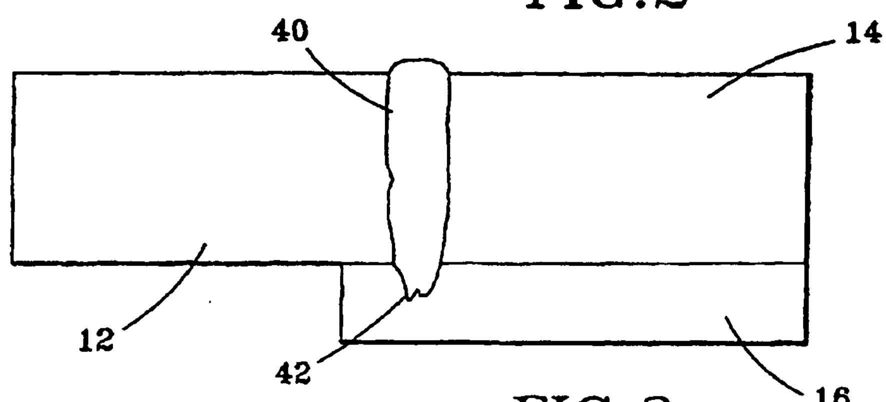

FIG.3

FIG. 4